Internal Waves in Straits Experiment

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LONG-TERM GOALS

To understand the generation, propagation and dissipation of large amplitude internal tides.

OBJECTIVES

To obtain time series and spatial structure of internal tidal propagation and evolution westward from the ridges in Luzon Strait as a component of the Internal Waves in Straits Experiment (IWISE).

APPROACH

Spatial and temporal variability of internal tidal generation and propagation may arise due to either changing background conditions (i.e., stratification, vorticity, mesoscale currents, and the Kuroshio Current) or interference patterns from multiple generation sites on the complex topography. Some of the largest internal tides in the ocean, with depth-integrated energy fluxes >60 kW m^{-1} (Figures 1–2), are generated at two parallel ridges in Luzon Strait (Alford et al., 2011; Simmons et al., 2011; Johnston et al., 2013). Averaging over many glider missions, considerable asymmetry is found between eastward and westward propagation into the Pacific Ocean or South China Sea (Rainville et al., 2013; Rudnick et al., 2013). Here we focus on the waves, which propagate westward into the South China Sea, steepen, and produce large-amplitude internal waves on the shallow thermocline.

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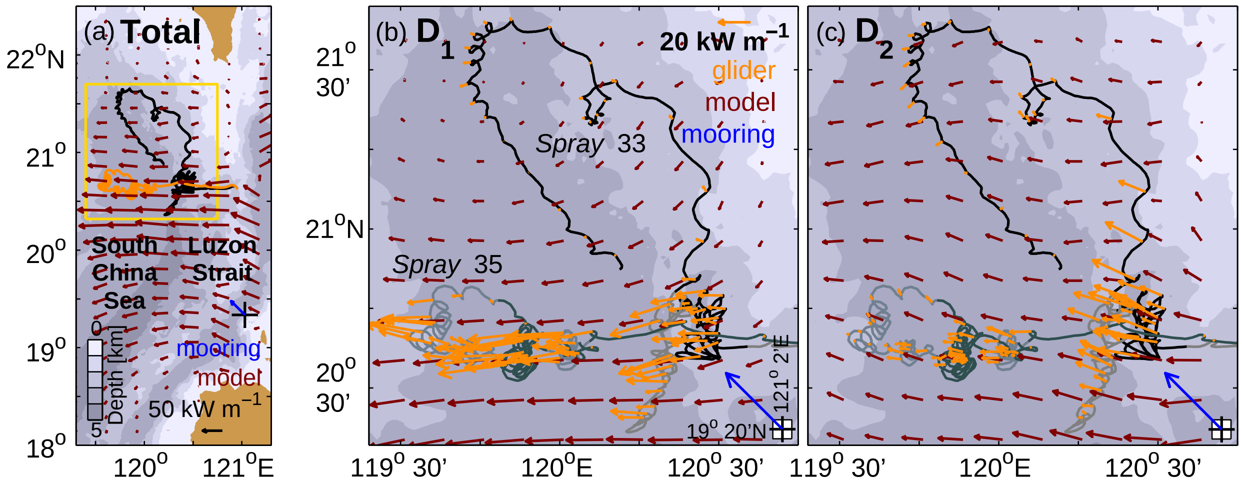

Figure 1: (a) Time-averaged, depth-integrated, mode-1 energy fluxes of 40–50 kW m^{-1} are generated at the ridges in Luzon Strait and propagate into the South China Sea from the model (red) and mooring (blue). Glider tracks (black and orange for Spray *33 and 35), mooring location (cross), and the region (yellow) in Figures 1b–c are also indicated. Bathymetry (grey shading), land (brown shading), and a scale vector are shown. (b) For D_1 and (c) D_2 constituents, depth-integrated, mode-1, baroclinic energy fluxes in the South China Sea are measured over spring and neap cycles by the gliders (orange) and are a one month time average from the model (red) and time-mean from the mooring (blue) over roughly the same period as the gliders. Glider fluxes are plotted at 1-day intervals. The glider tracks are plotted with alternating lighter and darker colours corresponding to alternating colours on the time axes in Figure 2. The mooring lies further south and the vector is inset (lower right).*

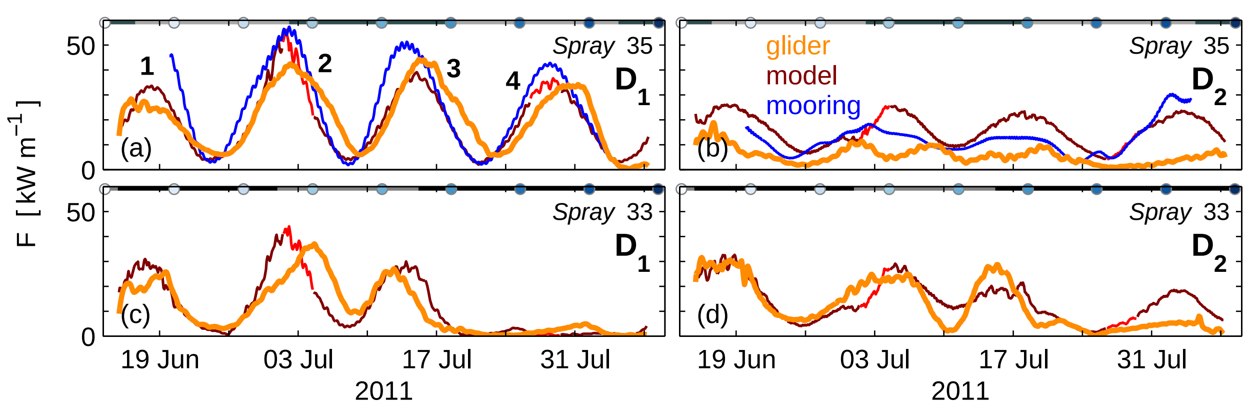

Figure 2: Depth-integrated, mode-1 energy flux magnitude from (a–b) Spray 35 and (c–d) Spray 33 for D_1 (left) and D_2 (right) are generally westward (Figure 1). Line colours denote gliders (orange), model (red), or mooring (blue). Spring tides are labelled 1–4 (Figure 2a). Areas of model overlap (light red) may suffer from edge effects.

In the face of such variability, extensive spatial coverage in the South China Sea and temporal coverage over spring-neap cycles is required to assess the generation and propagation of internal tides away from Luzon Strait. Two Spray underwater gliders, each equipped with an acoustic Doppler profiler (ADP) a conductivity-temperature-depth instrument (CTD), obtained internal tidal energy flux from tidally-resolving density and velocity measurements in the South China Sea. To our knowledge, this work is the first such calculation of energy flux from underwater gliders (Figures 1–2).

WORK COMPLETED

Two gliders observed the internal tide over four spring-neap cycles (13 June–8 August 2011) in the South China Sea. At five nominal sites along 20° 39′N, time series were obtained with each covering a spring-neap cycle. One glider took advantage of strong northward mean currents and surveyed the northern South China Sea. This capability to relocate during a mission allows for coverage in space and time.

For this project, Spray sampled every 6 s (or vertically <1 m) during ascents (Sherman et al., 2001). The payload included: (a) a pumped Sea-Bird Electronics (SBE) 41CP CTD to obtain temperature and salinity, from which potential temperature, in situ density, and potential density are calculated and (b) a Sontek 750 kHz ADP aligned to measure horizontal velocities in five 4-m vertical range bins. Over 2 months, a total of 1312 profiles were completed. Data and times are averaged in 10-m bins centered from 10–500 m. To resolve tides, the gliders dove at an angle of 30° from 0–500 m in depth every $\sim$2 hours on average.

Ongoing work aims to examine possible energy transfer from internal tides to high-frequency internal waves using our techniques developed during IWISE and NLIWI (Johnston et al., 2013; Rudnick et al., 2013).

RESULTS

As our primary technical result, we calculate mode-1 energy fluxes from velocity and density measurements by gliders which profiled rapidly enough to resolve the tides in the upper 500 m. Time series at five fixed locations and even while moving provide regional coverage over the northern half of the South China Sea using two gliders. The main limitation in our method is the lack of glider data below 500 m, which is mitigated by the shallow thermocline, the strong mode-1 signal, and fitting mode 1 to tidal currents and displacements. During spring tides, westward diurnal (D_1) and semidiurnal (D_2) mode-1 fluxes exceed 40 and 30 kW m^{-1}. As long as the thermocline is shallow enough to permit mode-1 fits, gliders can survey regional areas for internal tides with mode-1 flux estimates once every few days for $\sim$2 months.

Our primary scientific result concerns the stability of phase measurements over the observational period, which suggests a narrow-banded internal tide. Westward phase propagation is found for currents and displacements.

IMPACT/APPLICATIONS

In regions with relatively shallow thermoclines, gliders can assess mode-1 energy fluxes. Typically mode 1 carries much of the energy flux. Tidal phases appear stable over our time and space coverage of

2 months and 100 km.

Experience gained from the IWISE analysis to-date has proven useful in other observational efforts with gliders. Along with amplitude, phase has proven useful in diagnosing (a) D_2 internal tide propagation and reflection at the Tasmanian slope (next section) and (b) trapping of the D_1 internal tide off the California coast (Johnston and Rudnick, 2014). The trapped D_1 tide also appears as an important but perhaps underappreciated signal in these and other recent observations off California and Tasmania (next section).

Furthermore, we have made further use of the sampling strategy developed during IWISE of surveying a large area with a slowly-moving glider. This sampling takes advantage of the glider's slow speed, which restricts space-time confusion to a more limited wavenumber-frequency band (Rudnick and Cole, 2011). Results could be considered as a slowly-moving time series provided some averaging is used. More precisely, the D_1 and D_2 signals with wavelengths of order 100 km are smeared into observed wavenumbers of about 1/20–1/10 cycles km^{-1} (equation 5 in Rudnick and Cole, 2011), which is within our typical averaging window. For measuring these harmonic signals over a wide area, the gliders' slow motion is an advantage.

RELATED PROJECTS

An ONR project with Sarkar (UCSD) is using observational guidance from a number of observations of beams including ONR's AESOP (Johnston et al., 2011) and IWISE initiatives as the basis for investigating degradation in internal wave beams at in the surface layer (Gayen and Sarkar, 2013).

Techniques developed for gliders during IWISE have been further refined. They either have been or will be applied to other glider-based internal wave measurements (e.g. Johnston and Rudnick, 2014), such as sustained measurements along cross-shore lines off California.

The NSF-funded Tasmanian Tidal Dissipation Experiment (TTIDE) with many IWISE PIs (Pinkel, Alford, Johnston, MacKinnon, Nash, Rainville, Rudnick, and Simmons) is investigating reflection and dissipation of an incident low-mode internal tide impinging on the steep continental slope of Tasmania. Glider results show a relatively narrow (lateral) incident beam. A standing wave pattern is found near the Tasmanian slope with roughly equal incident and reflected wave energies.

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PUBLICATIONS

T. M. S. Johnston, D. L. Rudnick, M. H. Alford, A. Pickering, and H. L. Simmons. Internal tidal energy fluxes in the South China Sea from density and velocity measurements by gliders. *J. Geophys. Res. Oceans*, 118: 3939-3949, doi: 10.1002/jgrc20311, 2013.

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